

# AN HTR COGENERATION SYSTEM FOR INDUSTRIAL APPLICATIONS

B.R.W. HAVERKATE<sup>1</sup>, A.I. VAN HEEK  
Netherlands Energy Research Foundation ECN,  
Petten

J.F. KIKSTRA  
Thermal Power Engineering,  
Faculty of Mechanical Engineering,  
Delft University of Technology,  
Delft

Netherlands

## Abstract

*Because of its favourable characteristics of safety and simplicity the high-temperature reactor (HTR) could become a competitive heat source for a cogeneration unit. The Netherlands is a world leading country in the field of cogeneration. As nuclear energy remains an option for the medium and long term in this country, systems for nuclear cogeneration should be explored and developed. Hence, ECN Nuclear Research is developing a conceptual design of an HTR for Combined generation of Heat and Power (CHP) for the industry in and outside the Netherlands.*

*The design of this small CHP-unit for industrial applications is mainly based on a pre-feasibility study in 1996, performed by a joint working group of five Dutch organisations, in which technical feasibility was shown. The concept that was subject of this study, INCOGEN, used a 40 MW thermal pebble bed HTR and produced a maximum amount of electricity plus low temperature heat. The system has been improved to produce industrial quality heat, and has been renamed ACACIA. The output of this installation is 14 MW electricity and 17 tonnes of steam per hour, with a pressure of 10 bar and a temperature of 220 ° C. The economic characteristics of this installation turned out to be much more favourable using modern data.*

*The research work for this installation is embedded in a programme that has links to the major HTR projects in the world. Accordingly ECN participates in several IAEA Co-ordinated Research Programmes (CRPs). Beside this ECN is involved in the South African PBMR-project. Finally, ECN participates in the European Concerted Action on Innovative HTR.*

## 1. Introduction

### Background

The development of the helium cooled graphite moderated high-temperature reactor (HTR) is taking place for more than thirty years now. Safety studies have indicated that an HTR with spherical fuel elements has very favourable safety characteristics: the loss of coolant as well as graphite fires will not result in any significant fuel damage. Because of the relatively high temperatures of the system, the HTR would be very suitable as a heat source for combined generation of heat and power (CHP). This application complements major HTR developments elsewhere in the world: the South-African electric utility ESKOM is investigating the use of modular HTR reactors for expanding their electric generating capacity [1], and INET of China and JAERI of Japan are building an HTR test reactor for the development of nuclear process heat systems [2, 3].

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<sup>1</sup> Enquiries: Phone: + 31 224 56 4687  
email: [haverkate@ecn.nl](mailto:haverkate@ecn.nl)

In 1996, a joint working group in the Netherlands evaluated the technical and economical feasibilities of a nuclear cogeneration installation with a thermal power of 40 MW [4, 5, 6]<sup>2</sup>, which was based on the (Dutch) market demand for CHP-units.

### Cogeneration of Heat and Power

Forecasts on the future consumption and production of energy indicate an expanding world market for the combined generation of heat and power. This market for energy efficient CHP with overall capacity of 10 to 150 MW is particularly well developed in the Netherlands. In 1995, approximately 20 percent of the total electricity supply in the Netherlands has been generated by decentralised units and autoproducers. Another 33 percent has been generated by large natural gas fired power plants. Given the expected further depletion of the indigenous resources of natural gas (the fuel for CHP), a potential market could emerge for an alternate primary energy source within the next two decades, see figure 1. Nuclear energy could be one of the substitutes, if competitive prices and public acceptance for this new nuclear application can be achieved.

### Capacity [MWe]

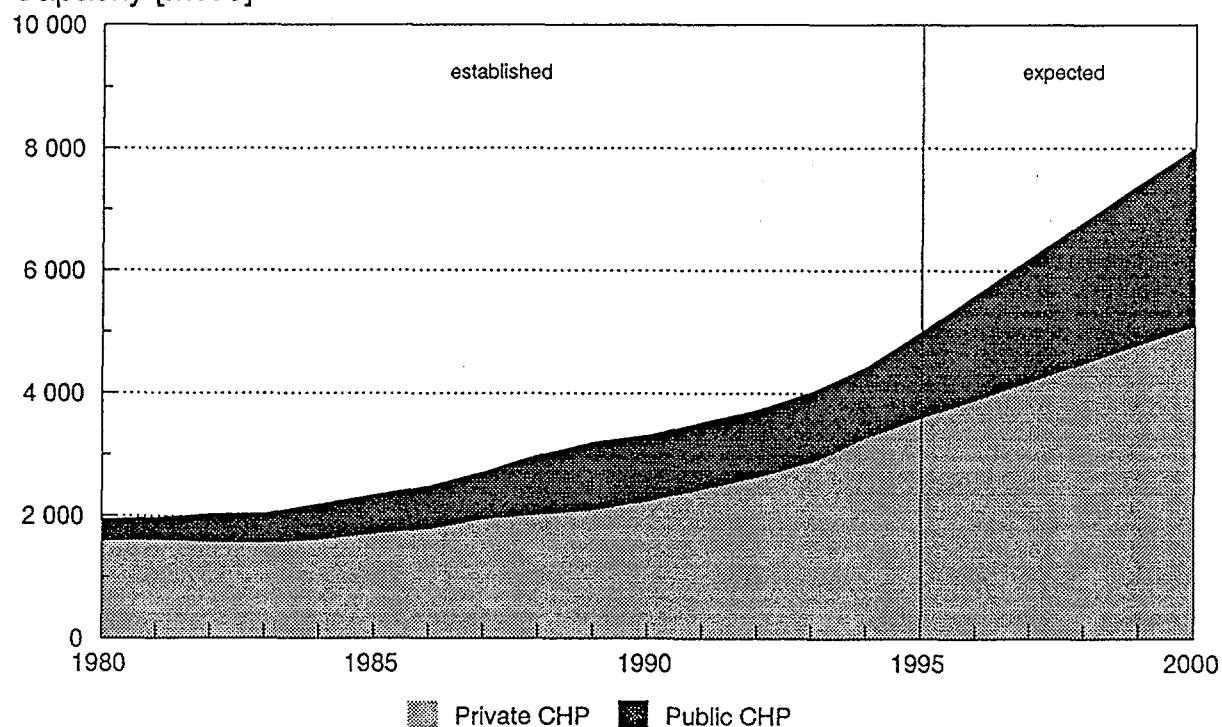


Figure 1: *Development of CHP in the Netherlands.*

### Reference Design for an Industrial Cogeneration Unit

The reference configuration of the CHP-unit is based on a reactor design by KFA Jülich, Germany [7], and an energy conversion system design by Longmark Power International (LPI) of Cambridge, USA [8]. One of the major results of the pre-feasibility study was, that there are no technological barriers to build a 40 MW thermal cogeneration unit. However a second look at economics, market potential and licensing aspects is highly recommended to establish this new breed of innovative reactor technology.

Consequently, the design features of the pre-feasibility study concept has been changed slightly to improve a small cogeneration unit for industrial applications with a heat output corresponding more to

<sup>2</sup> The summary report of the pre-feasibility study is also available on Internet:  
[http://www.ecn.nl/unit\\_nuc/research/htr/main.html](http://www.ecn.nl/unit_nuc/research/htr/main.html)

the needs of the (Dutch) industry in terms of steam amount and conditions. Beside this an electrical output of 13.6 MW will be delivered by the CHP-unit, named ACACIA, which is an acronym for AdvanCed Atomic Cogenerator for Industrial Applications.

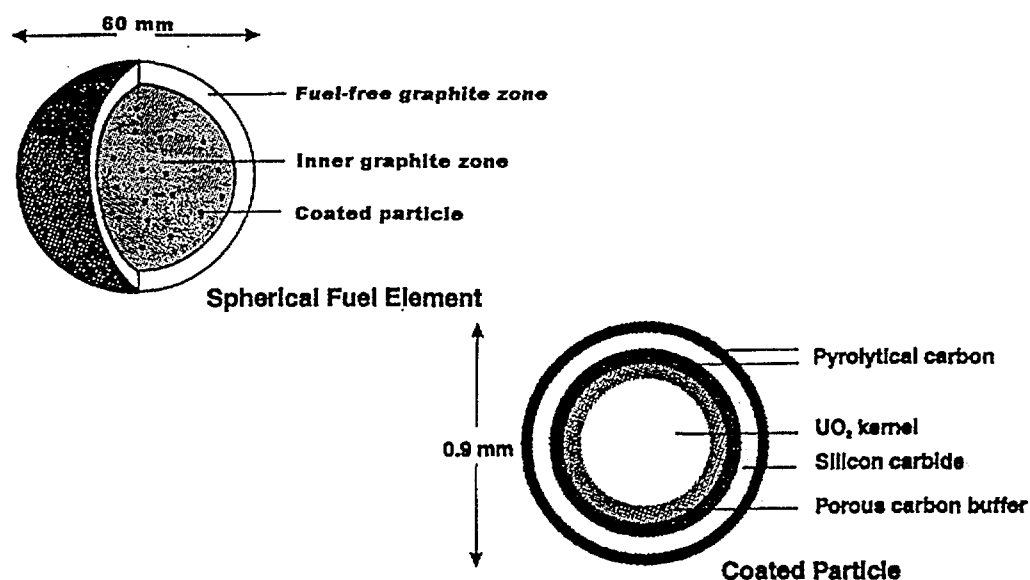
The design features of the ACACIA unit include:

- HTR based versatile heat source combined with a closed (Brayton) cycle energy conversion system,
- design thermal power of the reactor core of 40 MW,
- spherical fuel elements with a 60 mm diameter containing small (0.9 mm diameter) fuel particles according to the German TRISO design,
- loading mechanism of fuel into the core - as long as space allows - during operation, which is generally called the 'peu à peu' fuelling concept,
- resistance against accidents characterised by the two scenarios loss of flow and loss of coolant, both combined with an anticipated transient without scram (ATWS) condition,
- economic and simplified design by reduction of the systems, structures and components that need to meet nuclear qualification requirements.

## 2. Basis Configuration

The basis configuration of the ACACIA unit is a helium-cooled graphite moderated nuclear reactor with a thermal power of 40 MW and a core exit temperature of 800 °C. The nuclear power is generated in the reactor vessel which contains standard pebble bed HTR spherical fuel elements with a diameter of 60 mm, see figure 2.

The nuclear power is transferred to helium cooling gas which is pressurised to 2.3 MPa (23 bar). The helium is expanded to 1.0 MPa in a helium turbine. The turbine drives a helium compressor and generates electrical power in the attached generator. The expanded helium will be used to preheat compressed helium to increase the efficiency of the thermodynamic cycle and also for heat generation, through an intermediate helium circuit, for industrial applications. The remaining low-temperature waste heat will be rejected to the environment. The cooled-down helium will be compressed and directed to the reactor vessel where it will be heated again. The main design parameters of the conceptual ACACIA configuration are presented in table 1.

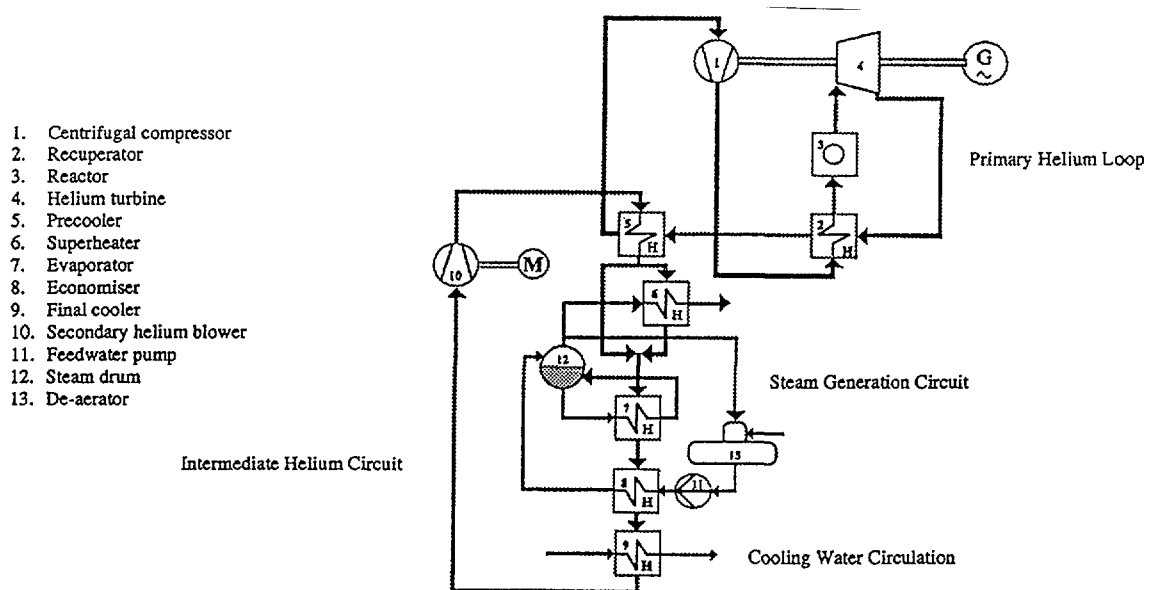


**Figure 2:** Fuel particles in spherical fuel elements [9]. About 11000 of these particles are embedded in the graphite matrix of a fuel element.

**Table 1: Main design parameters of ACACIA configuration.**

Characteristics of Main Components		Design Value
<b>Reactor</b>		
Thermal Power	MW	40
Operating Pressure	MPa	2.3
Helium Inlet / Outlet Temperatures	°C	494 / 800
Helium Mass Flow	kg/s	25
<b>Heat Cogeneration</b>		
Steam Inlet / Outlet Temperatures	°C	80 / 220
Steam Pressure	MPa	1
Steam Mass Flow	kg/s	4.7
Transferred Heat	MW	12
<b>Generator</b>		
Electrical Power	MW	13.6
<b>Overall Performance</b>		
Electric Efficiency ( $P_{\text{electric}}/P_{\text{reactor}}$ )	-	0.34
Heat Efficiency ( $P_{\text{heat}}/P_{\text{reactor}}$ )	-	0.30
Net Thermal Efficiency	-	0.64

The applied energy conversion system comprises a single-shaft turbine-compressor with a directly coupled electrical generator, see figure 3. The generator electrical power is 13.6 MW. An intermediate helium circuit heats a closed heat generation loop to deliver 17 tonnes per hour superheated steam of 1 MPa and 220 °C. The remaining heat is rejected to the environment through a circulation loop of cooling water.



**Figure 3: Main components of ACACIA cogeneration system.**

### 3. Technical Analyses

During the study to the feasibility of a cogeneration unit, in 1996, scoping analyses in the field of reactor physics, safety and graphite oxidation have been achieved, and extensively outlined in public reports [4, 5, 6], as well as during the previous IAEA Technical Committee Meeting at ECN, Petten [10]. Therefore, this paper will only describe a summary of the differences between the INCOGEN<sup>3</sup> configuration of the pre-feasibility study and the ACACIA system, arising from the in this study given recommendations.

#### Reactor Design

The fuel will be loaded into the core, as long as space allows, during operation in a manner that keeps the core only marginally critical. Void core volume can accommodate added fuel until defuelling. Because of the foreseen period for inspection and maintenance of the power conversion system and the reactor pressure vessel a defuelling interval of 3 years has been chosen for the ACACIA system (versus 10 years in the INCOGEN study). This reduction of the defuelling interval has advantages for the core dimensions, in particular a significant decrease of the core height is expected.

Safety relevant parameters like temperature coefficients and fuel temperatures for the most adverse heat-up conditions (LOCA, LOFA, ATWS) have been determined for the INCOGEN configuration. Since ACACIA uses the same core configuration, for the time being the ACACIA core safety behaviour is expected similar.

#### Energy Conversion System

One of the major changes of the ACACIA installation related to INCOGEN is the energy conversion system. The INCOGEN concept is optimised for almost maximum production of electricity, while industrial quality heat is the primary output of the ACACIA system. This results in a more suitable output of superheated steam for industrial applications, which is mainly driven through market potential reasons. A consequence of this optimisation to the heat production is less electrical power and a lower overall performance (see table 2). But, these disadvantages makes no odds against the much higher market potential of the cogeneration unit for industrial applications, and that therefore becomes a more realistic opponent to the conventional (natural gas fired) industrial CHP systems.

**Table 2: Energy Conversion System comparison.**

Main Energy Conversion System Design Parameters		Design Value	
		ACACIA	INCOGEN
<b>Heat Generation</b>			
Inlet / Outlet Temperatures	°C	80 / 220	40 / 150
Pressure	MPa	1	1
Transferred Heat	MW	12	18
Cogeneration Medium	-	Superheated steam	Hot water
<b>Generator</b>			
Electrical Power	MW	13.6	16.5
<b>Overall Performance</b>			
Heat Efficiency	-	0.30	0.45
Electric Efficiency	-	0.34	0.41
Power to Heat Ratio	-	0.88	0.92

<sup>3</sup> INCOGEN, which is an acronym for Inherently safe Nuclear COGENeration, is the name of the analysed configuration of the pre-feasibility study, in 1996. The primary output of this installation is 16.5 MW electricity. The remaining heat will be used for cogeneration applications, which heats an external pressurised water circuit from 40 °C to 150 °C, useable for low temperature industrial processes or district heating networks.

The flow diagram of the ACACIA unit is shown in figure 3. The helium is first compressed in a compressor (1) and flows subsequently through a recuperator (2), in which it is heated by the exhaust flow from the turbine. In this design, the recuperator could be omitted with very little loss of efficiency. However, the optimum pressure ratio would be much larger, leading to more expensive turbo-machinery. After the recuperator, the helium passes through the reactor-core (3), where it is heated. In the turbine (4), which drives the compressor and the generator, the helium is expanded. High speeds are allowed by application of a power electronic converter, which modulate the frequency to 50 Hz. Because of the converter, the shaft speed can be allowed to vary. An alternative for this single-shaft arrangement would be a twin-shaft system with free power turbine. Then a high-pressure turbine is used to drive the compressor, while a low-pressure turbine drives the generator. A synchronous generator could be used, but the low-pressure turbine would be much longer. The single-shaft system is thus chosen for reasons of simplicity. The helium leaving the turbine is cooled, first in the recuperator and later in the pre-cooler (5). In the pre-cooler, heat is transmitted to the intermediate helium circuit. In the steam drum (12), the intermediate helium first flows partly through a superheater (6). The bulk of the flow by-passes this heat-exchanger, because the steam has to be only slightly superheated. Then the helium flows through a natural convection evaporator (7) and an economiser (8). The flow is subsequently cooled in the final cooler (9) and compressed in the blower (10).

The influences on the plant efficiency of some variation have been established with a steady-state model [11]. In order to test the control-structure, a dynamic model is currently under construction<sup>4</sup>.

#### Plant Lay-Out

In figure 4 a cross section of the reactor and turbine building of an ACACIA unit is drawn<sup>5</sup>. The primary cycle of the energy conversion system is completely contained in a pressure vessel as shown in figure 5. The steam drum and final cooler are not shown in figure 4. This equipment is located on the same level as the gas-gas heat-exchangers and the turbo-machinery. The design of the secondary cycle is currently not integrated, but it is a simple series connection of tube and shell heat-exchangers.

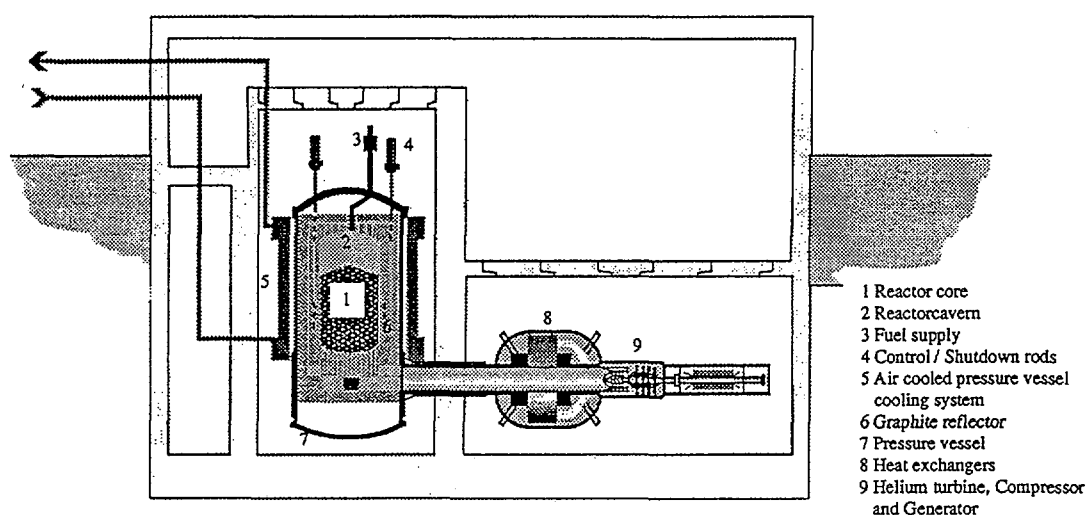


Figure 4: Cross Section Reactor and Turbine Building of ACACIA unit.

<sup>4</sup> See paper *Transient Analysis for the HTR Coupled to the Energy Conversion System* of E.C. Verkerk during this Technical Committee Meeting.

<sup>5</sup> Due to the somewhat shorter reactor pressure vessel the reactor building of the ACACIA plant is lower than for INCOGEN system.

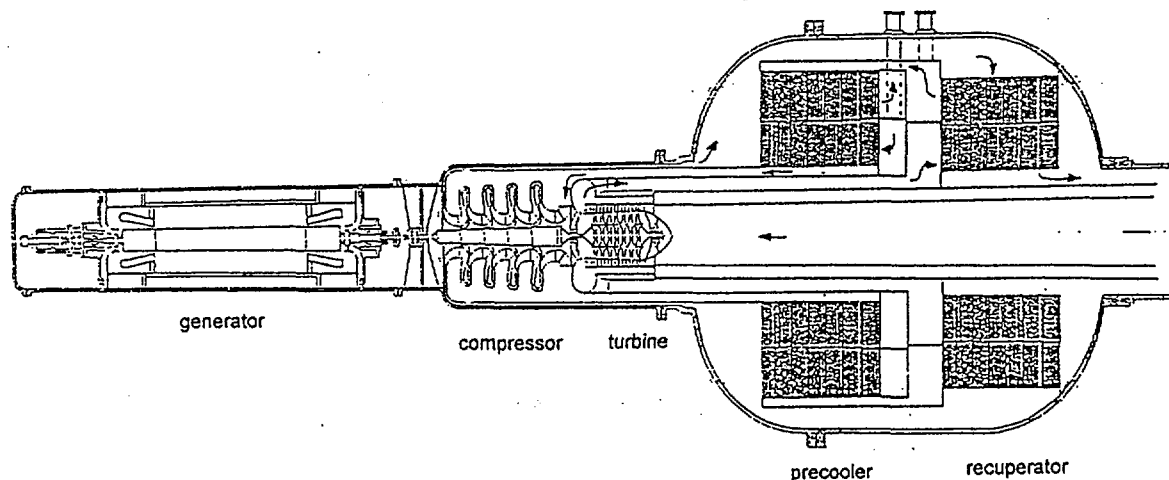


Figure 5: Schematic View Primary Cycle of the Energy Conversion System [11].

## 4. Economic Assessment

A reassessment of the economics was highly recommended in the INCOGEN pre-feasibility reports [4, 5], because the cost figures for INCOGEN were based on 'old fashioned' down-scaled Siemens data for the reactor and from down-scaled General Atomics data for the closed cycle helium turbine. This approach leads for the time being to the conclusion that the costs are too high compared to natural gas fired CHP units.

Hence, a second look to the economics has been carried out. This chapter will focus on these new cost estimates for an Nth-Of-A-Kind (NOAK) ACACIA system, which is based on recent cost data for the South African conceptual PBMR-design<sup>6</sup>, that have been presented during the previous IAEA Technical Committee Meeting [12].

In the INCOGEN pre-feasibility study the investment cost and production cost have been estimated at 8909 Netherlands Guilders (NLG) per produced kWe and 0.158 NLG per produced electrical kWh, respectively. A credit for the co-generated heat (based on the Dutch industry price for natural gas), and an annual discount rate of 10% for the capital costs have been taken into account. The new assessment shows that for the ACACIA unit, by scaling down recent South African cost data translated to the Dutch situation, these important key figures are reduced by 33% to 5961 NLG/kWe and 0.106 NLG/kWh, respectively [13]<sup>7</sup>. Due to the neglect of the simplified design of the smaller ACACIA system versus the PBMR an additional price reduction to be at least 20% are envisaged.

The production cost of an equally sized natural gas fired CHP unit is 0.057 NLG per kWh. Comparing the new economic figures with this amount indicates that a 40 MW thermal CHP unit will be entering the competitive area.

<sup>6</sup> Pebble Bed Modular Reactor system of 226 MWth for (100 MW) electricity production.

<sup>7</sup> To facilitate a comparison with the existing cost estimates, which was part of the INCOGEN pre-feasibility study, the same methodology is used in the current economic assessment. The scaling exponents are chosen in accordance to the publication "Nuclear Energy Cost Data Base" of the US Department of Energy, September 1988.

## 5. Links with International HTR-programmes

To establish an ACACIA unit, in the beginning of the next century, it is essential that the economical and technological research work is embedded in an international HTR network. Figure 6 shows the links of the Dutch HTR-project with the major HTR-activities in the world.

ECN participates in several IAEA Co-ordinated Research Programmes (CRPs) for safety calculations, defined by the IWGGCR<sup>8</sup>, on the Japanese HTTR<sup>9</sup> and the American / Russian GT-MHR<sup>10</sup> design. Besides this ECN is involved in the South African PBMR-project. Finally, ECN takes part, with partners from Germany, France, United Kingdom and Italy, in the European Concerted Action (CA) on Innovative HTR to define co-operative developments in the HTR field for the EU Fifth Framework Programme.

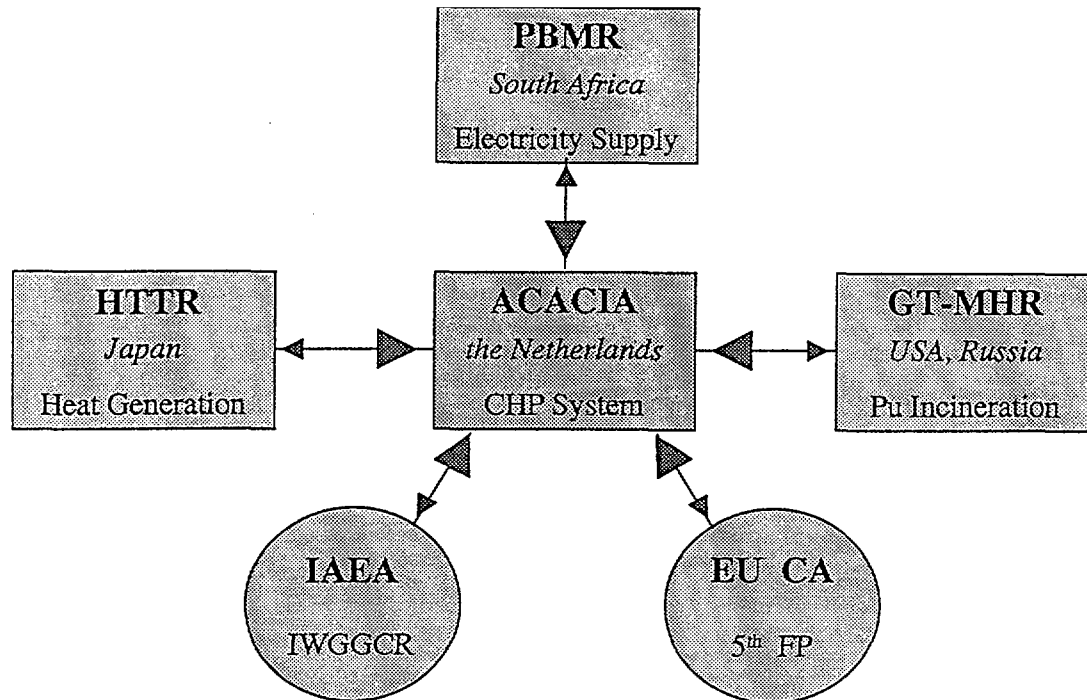


Figure 6: Links with major HTR projects in the world.

## 6. Conclusions

During the INCOGEN study, in 1996, technical feasibility of a 40 MW thermal cogeneration unit was shown. A reassessment of economics with modern data and a heat output corresponding more to the needs of the industry was highly recommended. Consequently, the INCOGEN concept has been changed slightly and has been renamed ACACIA.

ACACIA enters the competitive area with economics based on PBMR cost data translated to the Dutch situation. The superheated steam output (of 220 °C and 10 bar) is identified as interesting for a variety of heat consuming branches of industry.

<sup>8</sup> The IAEA International Working Group on Gas Cooled Reactors (IWGGCR) aims for the exchange of information between member states regarding their Gas Cooled Reactor (GCR) programme, and advises the IAEA on major research activities in the GCR field.

<sup>9</sup> High Temperature Test Reactor of 30 MW for heat generation [14].

<sup>10</sup> Gas Turbine - Modular Helium Reactor [15].



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